Selecting specific initial configuration using spectator neutrons in U+U collisions

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We present a method to select events with specific initial configuration, namely body-tip, in heavy-ion collisions using deformed Uranium nuclei. We propose to use asymmetry in spectator neutron numbers to filter out these body-tip events from the unbiased configurations in U+U collisions. We have used a variable S_η to differentiate between the body-tip and unbiased configurations. We have calculated the 2nd order azimuthal anisotropy, namely elliptic flow (v_2), for this body-tip configuration in the framework of a transport model and found it to be consistently lower compared to that in unbiased configurations as we expected. The purity of selecting such events in a real experiment is also discussed.

I. INTRODUCTION

In a central heavy-ion collisions with spherical nuclei such as Au or Pb, the initial overlap region is always circular. In the U+U collisions, however, the initial overlap region can acquire different configurations owing to the deformed shape of the Uranium nuclei [1]. In Ref. [1], the elliptic flow (v_2) has been studied and found to be strongly correlated with the different configurations of the initial overlap region. Moreover, in heavy-ion collisions, the energetic spectator protons can produce a strong magnetic field reaching $eB_y \sim m_\pi^2$ [2]. Such a strong magnetic field can give rise to chiral magnetic effect (CME) and chiral separation effect (CSE) [2, 3]. However, to observe these phenomena in real data, the azimuthal anisotropy (v_2) has to be minimised as it acts as a background [4] to these processes. Therefore, the events which have very high magnetic field and low azimuthal anisotropy (v_2) are the perfect candidates for the CME. In a central Au+Au or Pb+Pb collisions, the azimuthal anisotropy is very low, but the magnetic field is also low due to less number of spectator protons. In a non-central Au+Au or Pb+Pb collisions, although the magnetic field is comparatively high, the azimuthal anisotropy also (v_2) starts increasing and therefore, increasing the background to CME.
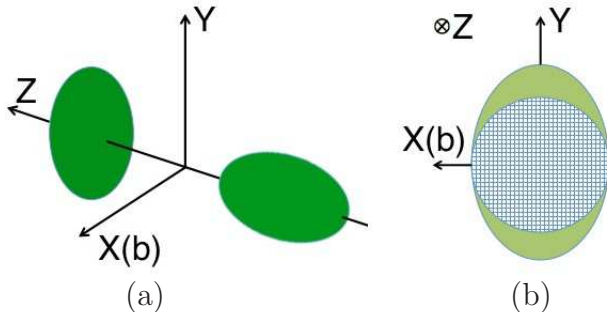

FIG. 1. (a) (Color online) Body-tip configuration in the laboratory frame of reference. The impact parameter is along the X-axis. (b) The cross sectional view of the overlap region (shown by mesh) for a central ($b = 0$) body-tip collision.

Due to the deformed shape, the U+U collisions can have unique orientations in which the magnetic field is very high in central collisions and as well as the azimuthal anisotropy is also very low. Therefore, U+U collisions may provide an unique opportunity to study these exotic effects in relativistic heavy-ion collisions. However, it has not been experimentally possible so far to unambiguously select specific configurations in U+U collisions.

In this paper, we propose a methodology to select body-tip configuration from unbiased events in U+U collisions. The body-tip configuration is pictorially shown in Figure 1(a), where the impact parameter is along X-axis and the beam direction is along Z-axis. In this configuration, the (right going) uranium nuclei whose major axis is perpendicular to beam is called body and other one (left going) whose major axis is along the beam is called tip [5]. As seen in Figure 1(b), the overlap region in such a body-tip collisions is circular (shown by mesh). The nucleons which lies in the overlap are called participants and those which lies outside the overlap region and do not take part in the collisions are called spectators. It is visible from Figure 1(b) that one uranium nucleus get completely occluded into the other, leaving almost no spectators, where as the other one will always have some spectator from the non-overlapping regions. This gives rise to asymmetry in the spectator counts in the two opposite directions. We use this particular feature of this body-tip event configuration to separate it out from rest of all the other random configurations possible in deformed uranium nuclei.

II. THE AMPT MODEL

We have used **A** **M**ulti **P**hase **T**ransport, namely the AMPT model, for our analysis. U+U collisions are implemented in the AMPT model by deforming the Woods-Saxon profile [6] as,

$$\rho = \frac{\rho_0}{1 + exp([r - R']/a)} \qquad (1)$$

$$R' = R[1 + \beta_2 Y_2^0(\theta) + \beta_4 Y_4^0(\theta)] \qquad (2)$$
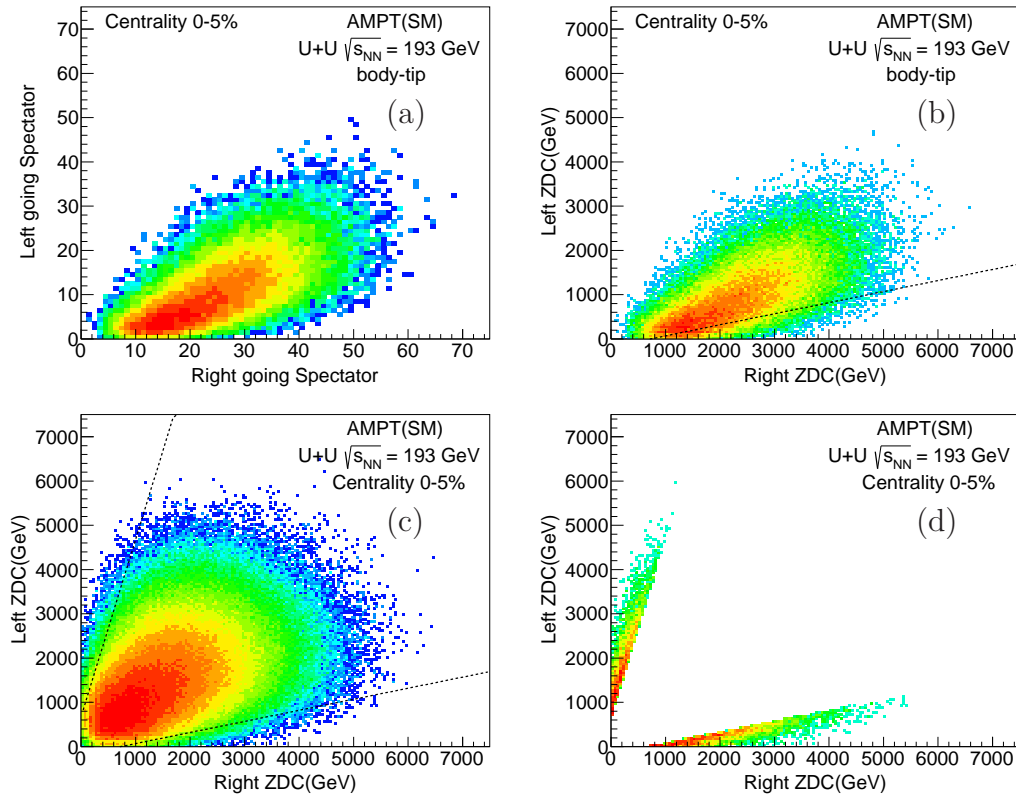
FIG. 2. (a) (Color online) Spectator neutron distribution for 0-5% central events in body-tip configuration of U+U collisions at $\sqrt{s_{NN}} = 193$ GeV. (b) Energy deposited by spectator neutrons in ZDC for the same events of body-tip configuration as in (a). (c) Energy deposited by spectator neutrons in ZDC for all configurations in U+U collisions. The dotted lines show the selection range for body-tip events. (d) The spectator neutron energy in ZDC after selecting events using the dotted lines in (c).

where ρ_0 is the normal nuclear density, R is the radius of the nucleus, and a denotes the surface diffuseness parameter. $Y_l^m(\theta)$ denote spherical harmonics and θ is the polar angle with respect to the symmetry axis of the nucleus. We have used the values of R, a, β_2 and β_4 from [1]. The AMPT model, which is a hybrid transport model, has four main stages: the initial conditions, partonic interactions, the conversion from the partonic to the hadronic matter, and finally hadronic interactions [7]. It uses the same initial conditions from HIJING [8]. Scattering among partons are modelled by Zhangs parton cascade [9], which calculates two-body parton scatterings using cross sections from pQCD with screening masses. In the default AMPT model, partons are recombined with their parent strings and when they stop interacting, the resulting strings fragment into hadrons according to the Lund string fragmentation model [10]. However in the string melting (SM) scenario, these strings are converted to soft partons and a quark coalescence model is used to combine parton into hadrons. The evolution dynamics of the hadronic matter is described by A Relativistic Transport (ART) model [11]. We have used string melting (SM) mode of AMPT version 2.25t7, with parton-parton cross section of 10 mb which will give rise to substantial amount of v_2. A total of 0.6 million 0-5% central events

were generated using this model for the analysis.

III. RESULTS AND DISCUSSION

In the experiments it is possible to get the measure of spectators using zero degree calorimeter (ZDC) detector which lies very close to the beam pipe in the forward (and backward) direction. The ZDC detector gives an electrical signal which is proportional to the number of spectator neutrons. Therefore, we will use only the neutrons from the spectators for our study. In Figure 2 we show the spectator neutron correlation for both body and tip oriented Uranium nuclei in body-tip collisions. As seen from the figure, the spectator neutron counts are not symmetric for body-tip collisions. In a real experiment, these spectator neutrons are detected by Zero Degree Calorimeters (ZDC). Therefore, it is worthwhile to convert this spectator neutrons into practically measurable ZDC signal. We use the ZDC response of STAR experiment from Ref. [12]. From Fig.6 of Ref. [12] we find that the resolution of single neutron ZDC response is 18%. Therefore, we smear the energy deposited by each individual spectator neutron by a Gaussian distribution with the width of 18% of the mean value to imitate the

response in the ZDC detector. The mean value of energy deposited by a single neutron for this study is 96.5 GeV. The energy deposited by the spectator neutrons in the ZDC, event by event, is shown in Figure 2(b). We can select the body-tip events from all the other configurations using this correlation shown in Figure 2(b). One such selection procedure is shown by the dotted line, with slope = 0.25 and intercept = -180. We select all the events which lies below this line, therefore selecting the events with asymmetric spectator neutrons. The ZDC response for all possible configurations in U+U collisions is shown in Figure 2(c). Since both left going and right going nuclei can be in either body or in tip orientation, therefore, we select these events along both (left and right) axis. Two dotted lines show the selection ranges for the possible body-tip events. Figure 2(d) shows the ZDC response of the selected events.

One way to differentiate between the minimum bias (all possible configurations) and the body-tip configurations is to look at the variable S_η which is defined as,

$$S_\eta = \frac{\sum \eta (dN/d\eta)}{N_{tot}} \quad (3)$$

where, N_{tot} is the number of particles within pseudorapidity range, $-1.0 < \eta < 1.0$ and the summation is over all particles in the event. Figure 3 shows the variable S_η as a function of N_{tot} for minimum bias, events selected with cuts on the ZDC signal from minimum bias configuration, and pure body-tip events. The S_η for minmum bias configurations lies close to zero, suggesting symmetry in particle production. The particle production in body-tip events are asymmetric in η as shown by solid squares in Fig. 3. Whereas, when selecting body-tip events from minimum bias configurations, both the projectile and the target can either be in body or in tip configuration. Therefore we have two set of S_η (when projectile is body, target is tip and vice-versa) for the selected events. The difference observed in S_η of selected events and minimum bias configurations enhances the possibility of our method to select the body-tip events in real experiments.

Now that we think we have potentially selected body-tip events from all configurations, we are going to look at v_2 of selected events. As the overlap region in a central body-tip collision is circular, therefore we expect that magnitude of the v_2 for selected events should be less compared to a set of events with an specific selection of configuration in U+U collisions. Figure 4 shows the v_2 of charged particles in mid-rapidity ($-1.0 < \eta < 1.0$), measured with respect to participant plane (Ψ_{pp}) for 0-5% central events in U+U collisions at $\sqrt{s_{NN}}$ = 193 GeV. The detailed method of calculating Ψ_{pp} using the position co-ordinates of participants (nucleons which take part in the collisions) is given in Ref. [13]. From Figure 4(a) we see that the v_2 in body-tip events is lower compared to minium bias configurations in U+U collisions. Now the selected body-tip events might also contain some small amount of other possible configurations of U+U collisions. Therefore, we have varied the slope of

the dotted line shown in Figure 2(c) to make the selection more strict or relaxed. The corresponding change in the v_2 is also shown in the Figure 4(a). The magnitude of charged particle $v_2(p_T)$ in the selected body-tip events
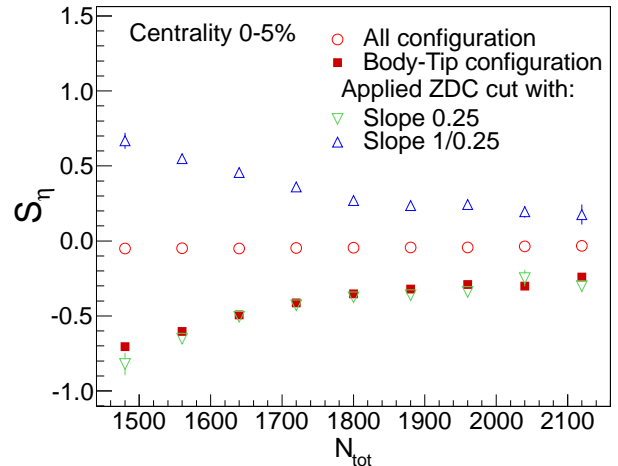

FIG. 3. (Color online) S_η (see Eqn. 3) for minimum bias, selected body-tip events from minimum bias, and pure body-tip events.

are systematically 25% lower than that in all configurations. The $v_2(p_T)$ for purely body-tip events (i.e., orientation of Uranium nuclei are fixed according to body and tip orientation) in AMPT is also shown as solid curve in Figure 4(a). The dotted and dashed lines in Figure 4(a) corresponds to the v_2 measured with respect to reaction plane angle (Ψ_r) in body-tip and selected body-tip events from all configurations respectively. The difference in the $v_2\{\Psi_r\}$ and $v_2\{pp\}$ shown in Figure 4(a) arises due the fluctuations in the initial participant distribution. The reaction plane angle Ψ_r is defined as the angle between the impact parameter and the X-axis and is a known quantity in the AMPT model. In experiments, however, the position of the participant nucleons are unknown. In this scenario, the event plane is calculated using the anisotropic distribution of the produced particles [14]. We followed η sub-event plane method to calculate v_2 of charged particles. In this method, each event is divided into two uncorrelated sub-events in two different η windows. Then 2nd order event plane (Ψ_2) is calculated separately in both of these sub-events. Each particle is then correlated with the event plane of opposite η so as to remove the self-correlation effect [14]. The v_2 result obtained in this method is then corrected for the η sub-event plane resolution [15]. We have followed event-by-event resolution correction [16] for our analysis. The details of the procedure of event plane calculation and resolution correction can be found in [17]. The $v_2\{EP\}$ results for 0-5% central U+U collisions, calculated with event plane method, are shown in Figure 4(b). The $v_2\{EP\}$ for all configuration is shown by open markers in Figure 4(b). The $v_2\{EP\}$ for different ZDC cuts are shown by solid markers. As seen in Figure 4(b), $v_2\{EP\}$ is also system-

atically 25% lower for selected body-tip events compared to $v_2\{EP\}$ of all configurations. The $v_2\{EP\}$ for purely body-tip events is shown by solid curve in Figure 4(b). As we see in Figure 4(b), with decreasing slope parameter (i.e., selecting events with higher spectator neutron asymmetry), $v_2\{EP\}$ of selected events systematically decreases compared to that of all configurations. Therefore, using lower slope value (higher spectator asymmetry), we can enhance the selection of body-tip events from all configurations in U+U collisions. Figure 4(c) and Figure 4(d) shows the distribution of the angle of the major axis of the Uranium with the beam axis for body (θ_b) and tip (θ_t) orientation for slope = 0.25. θ_b and θ_t for two different slope values and for all configuration in U+U collisions are also shown for comparison. Although lower slope values enhance the selection of body-tip events from all configuration, it also results in reduced event statistics. The selected events may possibly contain some other configurations. Therefore, we have calculated the purity of the selected events. By purity we infer that how much of the selected events can be specified as body-tip type events. Therefore, purity(%) = (number of selected events with θ_t, θ_p within the limits of relaxation θ_R) / (total number of events satisfying the ZDC cut)×100. Here we call an selected event to be body-tip if $-\theta_R < \theta_t < \theta_R$ and $(\pi/2 - \theta_R) < \theta_b < (\theta_R + \pi/2)$.

TABLE I. Purity (in %) of selected events for different slope parameter and angular relaxation (see text for details).

slope parameter / Angular relaxation (θ_R)	±10°	±20°	±30°
0.10	34%	62%	74%
0.15	28%	52%	70%
0.25	26%	48%	67%
0.35	24%	45%	63%

Since the angular distribution of both of the selected Uranium nuclei has some finite width, therefore, we assume that out of the selected events, the number of events for which θ_b and θ_t lies within $\pm\theta_R$ degree of the corresponding default values in body-tip events ($\theta_b = \pi/2$ and $\theta_t = 0$) is the pure body-tip sample. It is worth mentioning that the purity of the selected events depends on the relaxation on the angular width (θ_R) we set to classify the selected event as body-tip. Hence we calculated the purity of the selected event sample for different angular relaxation and the results are listed in Table I. As seen from Table I, the purity of selected events increases as we decrease the value of slope parameter or if we increase the angular relaxation. As can be found in Table I, more than 70% purity can be achieved using low slope value (i.e., higher order of spectator neutron asymmetry).

IV. SUMMARY

We present an experimental procedure to select the body-tip configuration among all possible configuration in 0-5% central U+U collisions at $\sqrt{s_{NN}} = 193$ GeV. We found that the spectator neutron energy deposited in the Zero Degree Calorimeter (ZDC) is a useful tool to select body-tip oriented events in central U+U collisions. We are able to select body-tip configuration with conditions applied on spectator neutron asymmetry simulated with the ZDC. We have used a new variable S_η to differentiate between the body-tip and the minimum bias configurations. Elliptic flow (v_2) is calculated for the selected events with respect to both participant plane angle (Ψ_{pp}) and event plane angle (Ψ_2). As expected, v_2 of selected events is found to be systematically lower compared to that in all configurations in U+U collisions. The ZDC selection cut (slope) was varied and it was found that selecting events with higher spectator neutron asymmetry results in lower v_2 values which tends to match with v_2 of pure body-tip events. Finally we calculated the purity of the selected events from all configurations in the U+U collisions. We observed that purity increases for decreasing slope parameter. In other words, if we apply cut selecting higher order of left-right spectator neutron asymmetry, then the purity of the selected events increases.

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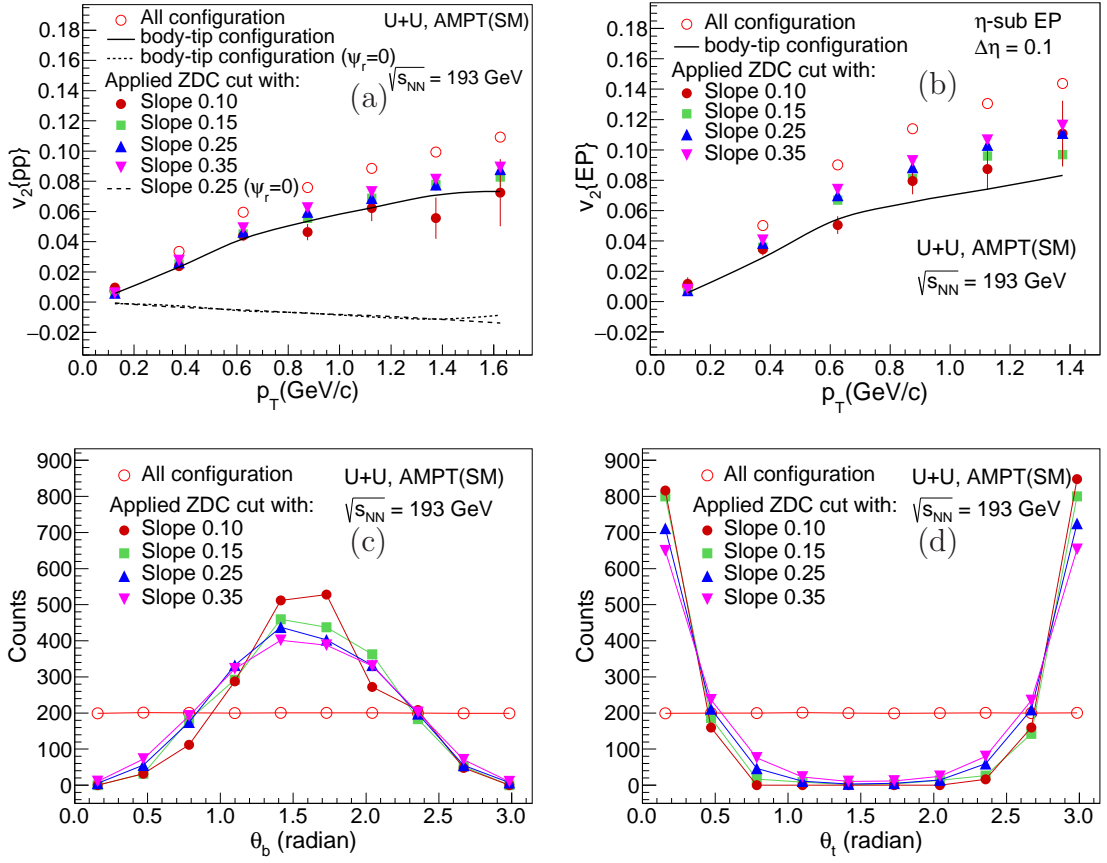
FIG. 4. (Color online) (a) $v_2\{pp\}$ for 0-5% central U+U collisions at $\sqrt{s_{NN}} = 193$ GeV without ZDC cut (open markers) and with ZDC cut (solid markers). (b) $v_2\{EP\}$ for the same events without ZDC cut (open markers) and with ZDC cut (solid markers). Solid line in (a) and (b) corresponds to v_{2pp} and v_{EP} for pure body-tip events. (c) Distribution of the angle of the major axis with the beam axis for body (θ_b) and for (d) tip (θ_t) oriented Uranium nuclei for different slope parameters. For pure body-tip events, $(\pi/2 - 0.005) < \theta_b < (\pi/2 + 0.005)$ and $0 < \theta_t < 0.05$ (radian).

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